

Physics of Schottky Electron Sources

Theory and Optimum Operation

Merijn Bronsgeest



Physics of Schottky Electron Sources



Physics of Schottky Electron Sources

Theory and Optimum Operation

Merijn Bronsgeest

Published by

Pan Stanford Publishing Pte. Ltd.
Penthouse Level, Suntec Tower 3
8 Temasek Boulevard
Singapore 038988

Email: editorial@panstanford.com

Web: www.panstanford.com

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library.

**Physics of Schottky Electron Sources:
Theory and Optimum Operation**

Copyright © 2014 by Pan Stanford Publishing Pte. Ltd.

All rights reserved. This book, or parts thereof, may not be reproduced in any form or by any means, electronic or mechanical, including photocopying, recording or any information storage and retrieval system now known or to be invented, without written permission from the publisher.

For photocopying of material in this volume, please pay a copying fee through the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, USA. In this case permission to photocopy is not required from the publisher.

ISBN 978-981-4364-79-9 (Hardcover)

ISBN 978-981-4364-80-5 (eBook)

Printed in the USA

Contents

<i>Preface</i>	ix
Introduction	1
1. Electron Emission from a Surface	7
1.1 The Potential Energy Barrier at a Surface	7
1.2 Emission by Heating	9
1.3 The Effect of an Electric Field on the Potential Energy Barrier at a Surface	12
1.4 Emission by Heating and Applying an Electric Field	16
1.4.1 Escape Probability	16
1.4.2 Current Density	22
1.4.3 Energy Distributions	25
2. Emission from a Schottky Emitter	29
2.1 Work Function Variations across the Emitter Surface	30
2.2 Applying a Bias	32
2.3 Applying a Heating Current	38
2.3.1 Temperature	38
2.3.2 Tip Protrusion (Field Strength)	42
2.3.3 Surface Properties (Work Function)	44
2.4 Total Emission Current	45
3. Emission from the End Facet	49
3.1 The Facet Extractor Lens	50
3.1.1 At the Facet	50
3.1.2 Lens Properties	52
3.1.3 Behind the Extractor	55
3.1.3.1 The angular intensity of the source	55
3.1.3.2 The full facet emission pattern	57
3.2 The Effect of the Voltage Settings	59
3.2.1 Different Options	59

3.2.2	The Effect of Changing the Extraction Voltage	60
3.2.2.1	From the facet toward the extractor	62
3.3	The Effect of Emitter Geometry	69
3.3.1	Tip End	69
3.3.2	Tip Size	71
3.3.3	Cone Shape	73
3.4	Schottky Plots	75
3.5	The Effect of the Heating Current	81
3.5.1	A Temperature-Dependent Work Function	84
3.5.2	The Predicted Effect on the Emission Pattern	89
4.	The Final Beam for Applications	95
4.1	Imaged by the Electron-Optical System: The Virtual Source	96
4.1.1	Imaginary Cold Schottky Source	97
4.1.2	Heated Schottky Source	100
4.2	Current in the Source Image: Practical Brightness	108
4.2.1	The Definition of Practical Brightness	109
4.2.2	How to Get the Practical Brightness of a Source?	113
4.2.3	The Intrinsic Practical Brightness for Thermionic, Schottky, and Cold Field Emission Electron Sources	114
4.3	Total Probe Size: Source Image Plus Diffraction Plus Aberration Contributions	116
4.4	The Effect of Electron–Electron Interactions in the Beam	119
4.4.1	Simulations	121
4.4.1.1	General equations	122
4.4.1.2	Application to Schottky emitters	125
4.4.1.3	Adding contributions together	130
4.4.2	The Boersch Effect Extracted from Energy Spread Data	134

4.4.2.1	Function to represent the Boersch effect	134
4.4.2.2	Total energy distribution measurement	135
4.4.2.3	Intrinsic contribution	136
4.4.2.4	Fit results	137
4.4.2.5	Comparison with theory	140
4.4.2.6	Discussion	141
4.5	Summarizing: The Beam Properties Relevant to Electron Optical Systems	142
5.	Geometrical Stability	147
5.1	Observed Geometrical Changes	147
5.2	Equilibrium Crystal Shapes	151
5.3	Tip Size Growth	156
5.3.1	The Continuum Model: Tip Size Growth at Low Fields	156
5.3.2	Tip Size Growth at High Fields	162
5.4	Changes of the End Facet Geometry	164
5.4.1	Evidence of the Tip-Emitter Interplay	165
5.4.2	Reversible Changes of the End Facet	168
5.4.2.1	Monitoring with the emission pattern	168
5.4.2.2	Monitoring with the Schottky plot slope	176
5.5	Collapsing of the End Facet	177
5.5.1	The Step-Flow Model	178
5.5.1.1	Application to Schottky emitters	182
5.5.1.2	Discussion	187
5.5.2	Tip-Emitter Interplay	189
5.5.2.1	Experiments	190
5.5.2.2	General system check: no-collapse operation	192
5.5.2.3	Collapsing analysis	193
5.5.3	(A)symmetry	196
5.5.4	Detailed Geometrical Description	201
5.6	The Effect on Beam Properties	208
5.6.1	Facet Size Changes	208
5.6.2	Facet Collapse	210

5.7	Concluding Remarks	211
6.	Optimum Operation	215
6.1	Maximum Performance for Different Applications	216
6.1.1	Maximum Performance from a Static Emitter Shape	216
6.1.2	Geometrical Limitations	220
6.2	Source-Monitoring Tools	224
6.2.1	Schottky Plot Slope	225
6.2.2	Total Emission Current	226
6.2.3	Facet Emission Pattern	226
6.3	Practical Considerations	227
6.3.1	For Users	227
6.3.2	For System Manufacturers and Experimental Setups	228
Appendix A.	Procedures for Monitoring in a Few Commercial Systems	231
Appendix B.	Procedure to Characterize System Performance	239
	Bibliography	243
	<i>Index</i>	251

Preface

The Schottky electron source is the predominant emitter type in focused electron beam equipment, but although used extensively and satisfactorily, its properties are not fully understood. New developments and increasingly more stringent performance requirements ask for a better understanding: What is the best possible performance from a Schottky source for a given application? Which operating parameters are associated with that performance, and how stable is this “best” performance? These are the questions addressed in this book.

The content for this book is the result of my work as a PhD candidate in the research group Charged Particle Optics at Delft University of Technology in the Netherlands, and it is my pleasure to acknowledge the interaction with Greg Schwind, Lyn Swanson, Sean Kellogg, and Alan Bahm of FEI Beamtech in Hillsboro, Oregon, USA, throughout the years; the technical assistance of Jan de Loeff, Frans Berwald, and Jacques Nonhebel of the research group Charged Particle Optics in Delft and of Ted Tessner of FEI Company; the opportunity given to me by Mike Lysaght and Greg Schwind of FEI Company to work with the sources research team of FEI Company in Hillsboro in May–July 2006; the courtesy of FEI Company for the use of some of its scanning electron microscopy (SEM) images in this book; the contributions to the work on practical brightness by the late Jim Barth of the research group Charged Particle Optics in Delft; and the support and guidance of my doctoral advisor Pieter Kruit, without whom this book would not exist.

Merijn Bronsgeest

Introduction

Electron beams are used for many applications. The most well-known example is probably the old-fashioned cathode ray tube (CRT) television, which changed our daily life. And an important step for science and technology was the invention of the electron microscope. Today's focused electron beam equipment uses electron beams mainly for imaging purposes, elemental characterization, and writing.

With respect to imaging or chemical analysis, electron irradiation of a sample produces a wealth of different signals for detection, each with specific information on the sample, for example:

- elastically back-scattered electrons;
- secondary electrons (ejected from the sample by inelastic scattering interactions with the beam electrons);
- Auger electrons (a beam electron removes an electron from the core of an atom, leaving a vacancy, an electron from a higher energy level falls into the vacancy, and the energy that is released is transferred to another electron, which is ejected from the atom with a characteristic kinetic energy);
- characteristic X-rays (a beam electron removes an electron from the core of an atom, leaving a vacancy, an electron from a higher energy level falls into the vacancy, and the energy that is released is transferred to a photon);
- light (a beam electron promotes an electron from the valence band to the conduction band (semiconductor sample), leaving a hole, and the electron recombines with a hole and emits a photon); and
- whether the sample is thin enough: transmitted electrons, which can be analyzed on changes in amplitude, phase, and/or energy with respect to the primary beam.

“Writing” with electrons is used, for example, to:

- locally functionalize a surface;
- create a charge pattern on the surface (for nanoxerography);
- locally expose a so-called “resist” layer on the surface (maskless lithography); and
- selectively deposit (part of) a precursor gas (electron beam-induced deposition [EBID]) (resistless nanolithography).

Crucial to any application is the electron source. The predominant emitter type in today’s focused electron beam equipment, and the topic of this book, is the so-called Zr/O/W{100} Schottky electron source.

Schottky electron sources are used in many different systems of different companies (e.g., FEI Company*, Jeol Ltd., Hitachi Ltd., Carl Zeiss, KLA-Tencor Corporation, Tescan s.r.o., Phi [Physical Electronics Inc.], RIBER, Applied Materials). To name a few examples: the Titan (scanning) transmission electron microscope (FEI Company), the Nova NanoSEM scanning electron microscope (FEI Company), the JBX-6300FS Electron Beam Lithography System (Jeol), the SU-70 scanning electron microscope (Hitachi), the JXA-8500F Electron Probe Micro Analyzer (Jeol), the Mira II CS scanning electron microscope (Tescan), the PHI 700 Scanning Auger Nanoprobe (Physical Electronics), and the microscopes with the Gemini column (Carl Zeiss).

Each of the applications puts its own specific demands on the properties of the irradiation. To give two examples, in electron energy loss spectroscopy (EELS) material-specific information is obtained by measuring the loss in energy of the primary beam electron upon transmission through the sample, and the primary beam electrons thus preferably all have exactly the same energy, while for high-resolution imaging it is desirable to be able to focus the electron beam down to a very small spot on the sample with still enough primary electrons in it to generate a detectable signal within a reasonable amount of time. The latter requires a high reduced brightness of the beam.

Over the past decades the Schottky source has been used as an electron emitter extensively and satisfactorily. Its properties, however, are not fully understood, and the ongoing quest for ever

*FEI Beam Technology Division, 5350 NE Dawson Creek Dr., Hillsboro, OR 97124, USA.

higher resolution and throughput, in combination with the advances made in the quality of electron optical systems (e.g., aberration correctors), put an increasing demand on the performance of the source with respect to, for example, brightness, energy spread, and geometrical stability. Examples are the recent interest in multibeam and multisource systems (Zhang & Kruit, 2007; Dokania *et al.*, 2008), the TEAM project (Dahmen *et al.*, 2009), and the MagellanTM (Young, 2009).

Such developments require better knowledge of the relation between the operating parameters of the source and the properties of the beam at the sample, and the stability of the physical shape of the emitter. These are the topics addressed in this book.

The Schottky source is typically operated in a vacuum environment of $\sim 10^{-9}$ mbar, and the electron emission is generated by heating the source and applying an electric field to it. Figure i.1 gives images of the Schottky emitter at different length scales.

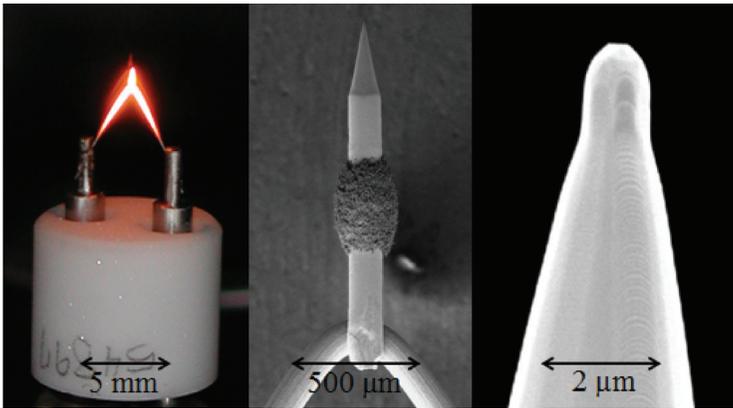


Figure i.1 Schottky emitters at different length scales.

The emitter consists of a single-crystalline tungsten wire, about 1 mm long and $125\ \mu\text{m}$ in diameter. One end of the wire is etched down to a tip with a diameter of about $1\ \mu\text{m}$. Halfway along the wire a reservoir of ZrO_x is attached, and at the other end the wire is spot-welded to a polycrystalline tungsten loop. This loop is fixed to two poles, which are embedded in a cylindrical ceramic base 1 cm in diameter. By running 2.0–2.5 A of current through the loop the emitter is heated through resistive heating and thermal conduction.

At a standard operating temperature of 1,800 K the emitter and part of the tungsten loop are glowing brightly.

The electric field is applied by biasing the emitter negatively with respect to an extractor: a metallic plate or cone, with a central aperture, usually at about 0.5 mm distance from the emitter tip. The potential difference between the emitter and the extractor is typically a few kilovolts. In the standard configuration the emitter is operated with an extractor and a suppressor.

The suppressor is a metal cap with a small hole. The emitter protrudes from the suppressor cap through the aperture for about 0.25 mm. It can be seen just peeking out from the cap in Fig. i.2. In operation the suppressor is biased negatively with respect to the emitter up to a few hundred volts to suppress unwanted electron emission from the part of the emitter that is inside the cap.

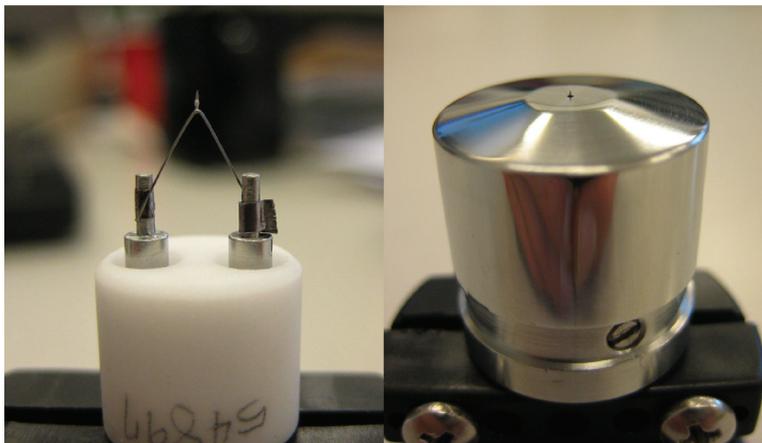


Figure i.2 Schottky emitter with and without a suppressor cap.

Two examples of a suppressor-emitter-extractor module are shown in Fig. i.3.

Characteristic for the Schottky emitter is the low work function of the planes with the $\{100\}$ orientation. This is caused by the presence of zirconium and oxygen on the surface, which reduces the work function of the $\{100\}$ planes considerably with respect to other crystallographic orientations. Zirconium and oxygen are present in the reservoir on the base of the emitter, and at a high operating temperature they can reach the $\{100\}$ planes through diffusion.

The most important $\{100\}$ plane is the facet on the tip end (Fig. i.1). This facet delivers the electrons that will end up in the final beam for applications. Most of the emission from a Schottky source is not used: the total emission from a Schottky emitter is typically up to a few hundred microamperes. The emission from the end facet is typically a few tens of microamperes. The beam current that is used in applications is cut out from the facet beam and typically contains of the order of a few picoamperes up to maybe microamperes.



Figure i.3 Examples of integrated source-suppressor-extractor modules (left: YPS AES-170 module; right: Denka TFE module).

The Schottky source has been studied by several investigators. In total about 50 articles have been published. Swanson *et al.* have done a great deal of the pioneering work from the late sixties to the mideighties in the area of Portland, Oregon. This area is still a location of active research: it is where FEI Company has concentrated its emitter research and development efforts. FEI Company is one of the few manufacturers of Schottky emitters (others are Denka and York Probe Sources Ltd.).

The first patent on the Schottky source was filed in 1964 as a result of the research in Oregon. Since then, about 15 US patents have been awarded, mainly to FEI Company (Oregon), Hitachi Ltd. (Tokyo), and Denka (Tokyo), although three early patents are from Wolfe, who worked for General Electric Company (New York) and Burroughs Corporation (Detroit).

During the work for this book there have been many discussions with FEI Company.

The structure of this book is as follows: in the first part of this book beam properties are addressed. Chapter 1 gives the electron emission theory that is used throughout this book to quantify the properties of emission from a surface. Chapter 2 addresses how the input parameters for emission theory relate to the practical case of a Schottky emitter in operation. In Chapter 3 we zoom in onto the emission from the end facet and how that arrives at the extractor, and in Chapter 4 we make the connection between facet emission and the final beam properties relevant to applications.

The second part, Chapter 5, is dedicated to the geometrical stability of the shape and consequences for the properties of the beam.

Finally, in the last part, Chapter 6, the focus is on achieving and maintaining maximum performance from the source for different applications.

The Schottky effect, the lowering of the potential barrier at the surface by applying a field to it, plays an important role in the emission properties of the Schottky electron source (Fig. i.4).

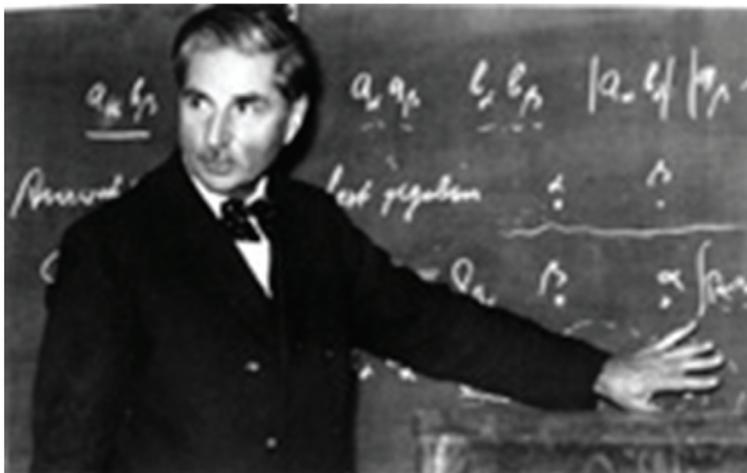


Figure i.4 Walter Hermann Schottky (1886–1976).